Upgrades to the ISS Water Recovery System

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The ISS Water Recovery System (WRS) includes the Water Processor Assembly (WPA) and the Urine Processor Assembly (UPA). The WRS produces potable water from a combination of crew urine (first processed through the UPA), crew latent, and Sabatier product water. The WRS has been operational on ISS since November 2008, producing over 21,000 L of potable water during that time. Though the WRS has performed well during this time, several modifications have been identified to improve the overall system performance. These modifications can reduce resupply and improve overall system reliability, which is beneficial for the ongoing ISS mission as well as for future NASA manned missions. The following paper lists these modifications, how they improve WRS performance, and a status on the ongoing development effort.

I. Introduction

The International Space Station (ISS) Water Recovery and Management (WRM) System insures availability of potable water for crew drinking and hygiene, oxygen generation, urinal flush water, and payloads as required. To support this function, waste water is collected in the form of crew urine, humidity condensate, and Sabatier product water, and subsequently processed by the Water Recovery System (WRS) to potable water. This product water is provided to the potable bus for the various users, and is stored in water bags for future use when the potable bus needs supplementing. The WRS is comprised of the Urine Processor Assembly (UPA) and Water Processor Assembly (WPA), which are located in two International Standard Payload Racks (ISPRs) named WRS#1 and WRS#2. This hardware was delivered to ISS on STS-126 on November 14, 2008 and initially installed in the US Lab module. On February 18, 2010, the racks were transferred to their permanent home in the Node 3 module.

II. Description of the ISS Water Recovery System

The ISS WRS provides the capability to receive the waste water on ISS (crew urine, humidity condensate, and Sabatier product water), process the waste water to potable standards via the WRS, and distribute potable water to users on the potable bus. A conceptual schematic of the WRS is provided in Figure 1. The waste water bus receives humidity condensate from the Common Cabin Air Assemblies (CCAAs) on ISS, which condenses water vapor and other condensable contaminants and delivers the condensate to the bus via a water separator. In addition, waste water is also received from the Carbon Dioxide Reduction System. This hardware uses Sabatier technology to produce water from carbon dioxide (from the Carbon Dioxide Removal Assembly (CDRA)) and hydrogen (from the electrolysis process in the Oxygen Generation System). Waste water is typically delivered to the WPA Waste Tank, though the Condensate Tank located in the US Laboratory Module is available in the event the WPA Waste Tank is disconnected from the waste bus.

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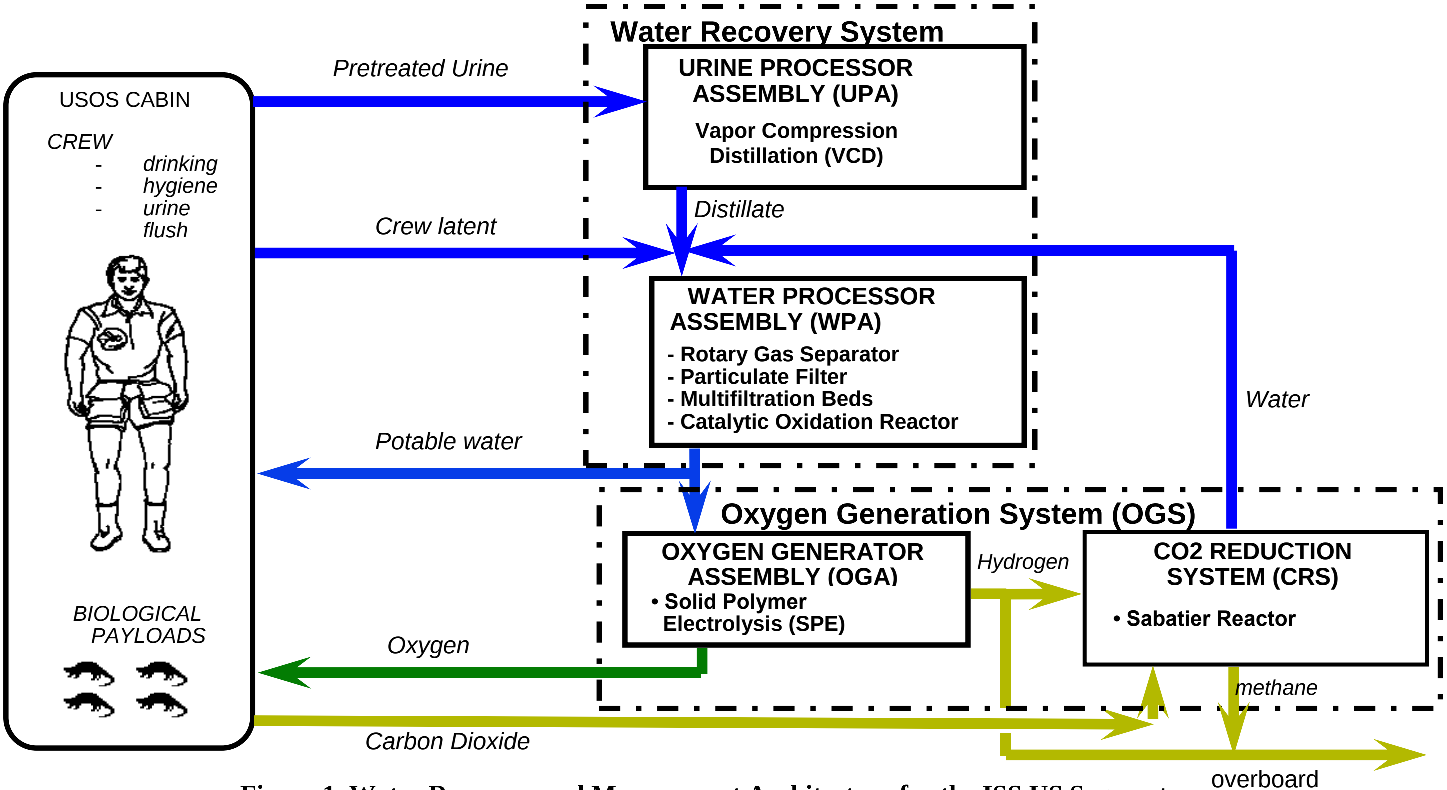


Figure 1. Water Recovery and Management Architecture for the ISS US Segment

The layout of the two WRS racks is shown in Figure 2, along with the OGS. The WPA is packaged in WRS Rack #1 and partially in WRS Rack #2, linked by process water lines running between the two racks. The remaining portion of WRS Rack #2 houses the UPA.

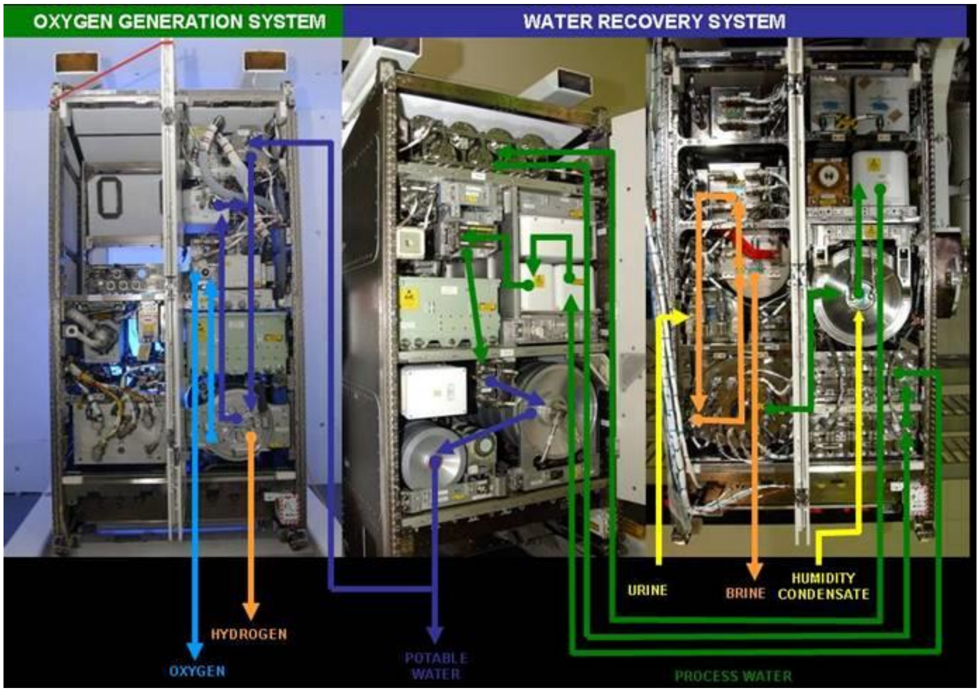


Figure 2. International Space Station Regenerative ECLSS Racks

A. Water Processor Assembly Overview

A simplified schematic of the WPA is provided in Figure 3. The WPA is packaged into 16 Orbital Replacement Units (ORU), and occupies WRS#1 and the right half of WRS#2. Wastewater delivered to the WPA includes condensate from the Temperature and Humidity Control System, distillate from the UPA, and Sabatier product water. This wastewater is temporarily stored in the Waste Water Tank ORU. The Waste Water Tank includes a bellows that maintains a pressure of approximately 5.2 – 15.5 kPa (0.75 to 2.25 psig) over the tank cycle, which serves to push water and gas into the Mostly Liquid Separator (MLS). Gas is removed from the wastewater by the MLS (part of the Pump/Separator ORU), and passes through the Separator Filter ORU where odor-causing contaminants are removed from entrained air before returning the air to the cabin. Next, the water is pumped through the Particulate Filter ORU followed by two Multifiltration (MF) Beds where inorganic and non-volatile organic contaminants are removed. Once breakthrough of the first bed is detected, the second bed is relocated into the first bed position, and a new second bed is installed. The Sensor ORU located between the two MF beds determines when the first bed is saturated based on conductivity. Following the MF Beds, the process water stream enters the Catalytic Reactor ORU, where low molecular weight organics not removed by the adsorption process are oxidized in the presence of oxygen, elevated temperature, and a catalyst. A regenerative heat exchanger recovers heat from the catalytic reactor effluent water to make this process more efficient. The Gas Separator ORU removes excess oxygen and gaseous oxidation by-products from the process water and returns it to the cabin. The Reactor Health Sensor ORU monitors the conductivity of the reactor effluent as an indication of whether the organic load coming into the reactor is within the reactor's oxidative capacity. Finally, the Ion Exchange Bed ORU removes dissolved products of oxidation and adds iodine for residual microbial control. The water is subsequently stored in the Water Storage Tank prior to delivery to the ISS potable water bus. The Water Delivery ORU contains a pump and small accumulator tank to deliver potable water on demand to users. The WPA is controlled by a firmware controller that provides the command control, excitation, monitoring, and data downlink for WPA sensors and effectors.

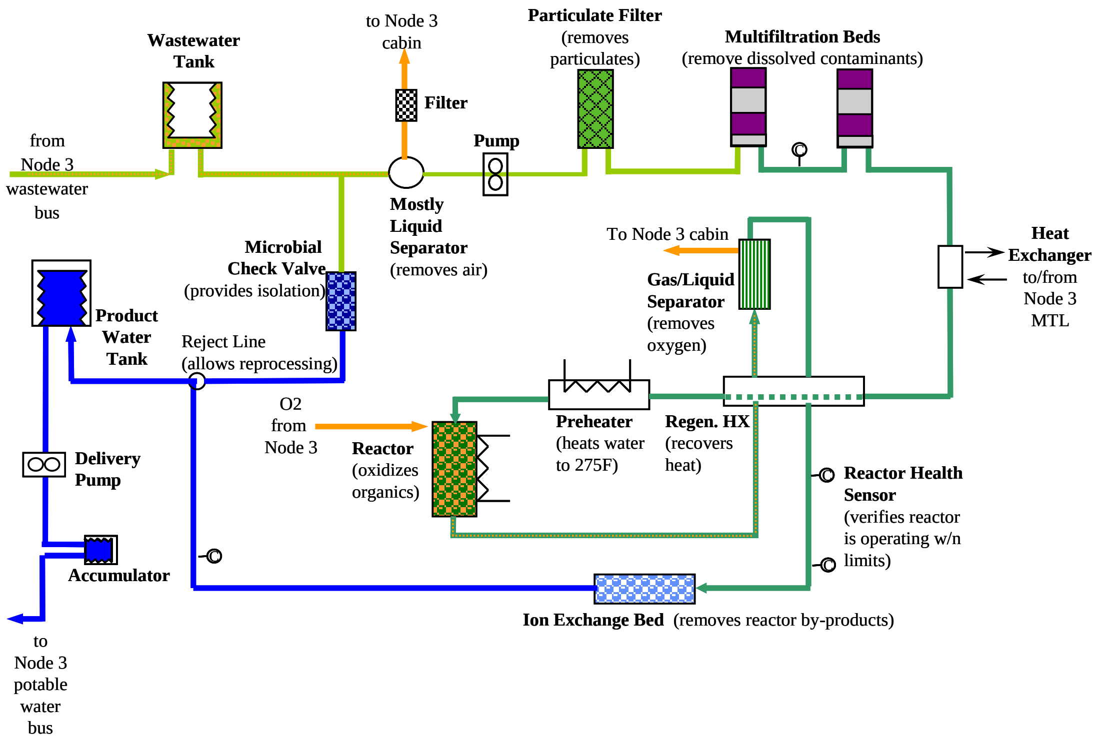


Figure 3. WPA Simplified Schematic

B. Urine Processor Assembly Overview

A simplified schematic of the UPA is shown in Figure 4. The UPA is packaged into 7 ORUs, which take up 60% of the WRS Rack #2. Pretreated urine is delivered to the UPA either from the USOS Waste and Hygiene Compartment (outfitted with a Russian urinal) or via manual transfer from the Russian urine storage container (called an EDV). In either case, the composition of the pretreated urine is the same, including urine, flush water, and a pretreatment formula containing chromium trioxide and sulfuric acid to control microbial growth and the reaction of urea to ammonia.

Figure 4. Urine Processor Assembly Schematic

Urine enters the UPA and is temporarily stored in the Wastewater Storage Tank Assembly (WSTA) until enough has accumulated to automatically initiate a process cycle. The Fluids Control and Pump Assembly (FCPA) is a four-tube peristaltic pump that moves urine from the WSTA into the Distillation Assembly (DA), recycles the concentrated waste from the DA into the Advanced Recycle Filter Tank Assembly (ARFTA) and back to the DA, and pumps product distillate from the DA to the wastewater interface with the WPA. The DA is the heart of the UPA, and consists of a rotating centrifuge where water from the waste urine stream is evaporated at low pressure. The water vapor is compressed and subsequently condensed on the opposite side of the evaporator surface to conserve latent energy. A rotary lobe compressor provides the driving force for the evaporation and compression of water vapor. Waste brine resulting from the distillation process is stored in the ARFTA, which is a bellows tank that can be filled and drained on ISS. The ARFTA has less capacity (approximately 22 L) than the previously used Recycle Filter Tank Assembly (RFTA) (41 L), but the capability to fill and drain the ARFTA on ISS avoids the costly resupply penalty associated with launching replacement RFTAs. When the brine is concentrated to the required limit, the ARFTA is emptied into an EDV, a Russian Rodnik tank on the Progress vehicle, a Temporary Urine and Brine Stowage System (TUBSS) bag, or into the water tanks on the ATV vehicle. The ARFTA is later refilled with pretreated urine, which allows the process to repeat. The Pressure Control and Pump Assembly (PCPA) is another four-tube peristaltic pump which provides for the removal of non-condensable gases and water vapor from the DA. Liquid cooling of the pump housing promotes condensation, thus reducing the required volumetric capacity of the peristaltic pump. Gases and condensed water are pumped to the Separator Plumbing Assembly (SPA), a hydrophobic membrane liquid/gas separator which returns water from the purge gases to the product water stream and vents air back into the cabin. A Firmware Controller Assembly (FCA) provides the command control, excitation, monitoring, and data downlink for UPA sensors and effectors.

The UPA was designed to process a nominal load of 9 kg/day (19.8 lbs/day) of wastewater consisting of urine and flush water, this is the equivalent of a 6-crew load on ISS. Product water from the UPA has been evaluated on the ground to verify it meets the requirements for conductivity, pH, ammonia, particles, and total organic carbon. The UPA was designed to recover 85% of the water content from the pretreated urine, though issues with urine quality encountered in 2009 have required the recovery to be dropped to a maximum of 75%. These issues and the effort to return to 85% recovery are addressed in the discussion on UPA Status.

III. WPA Upgrades

The WPA has been a reliable system on ISS that has consistently met potable water quality requirements. However, the WPA has experienced several anomalies that must be addressed for future systems. First, biomass growth in the WPA waste tank has accumulated over time, and is periodically sloughed into the process water as the waste tank bellows is filled and emptied. This effect resulted in a clogged solenoid valve in 2010, and is now mitigated with a mechanical filter downstream of the tank that must be periodically replaced. The next generation WPA must address this event by either controlling the growth of biomass or designing the waste water plumbing and valves to accommodate biomass.

Second, the WPA process pump has failed twice due to mechanical binding. The first failure occurred due to a design issue that allowed the internal radius of the gears to loosen on the shaft, eventually causing the gears to contact the pump housing and bind. The second failure occurred because the alumina gears formed an oxide that prevented pump operation when initially installed on ISS. These failures are discussed in more detail elsewhere [1], but illustrate reliability concerns with this pump design. Though the WPA engineering team believe the gear pump is viable for long-term manned missions, it is desirable to evolve the WPA to a system that can implement a more reliable pump design. The current pump design is driven by the fact that the WPA Catalytic Reactor operates at a temperature of 267 ºF, which requires a pressure of approximately 60 psig to avoid boiling. A viable system upgrade would be the development of catalyst that can effectively oxidize the influent organic load at a temperature less than 212 ºF, allowing the system to operate at ambient pressure. This would eliminate the high pressure pump and allow the implementation of a pump design that is inherently more reliable. The development of catalyst to support this objective is discussed in more detail below.

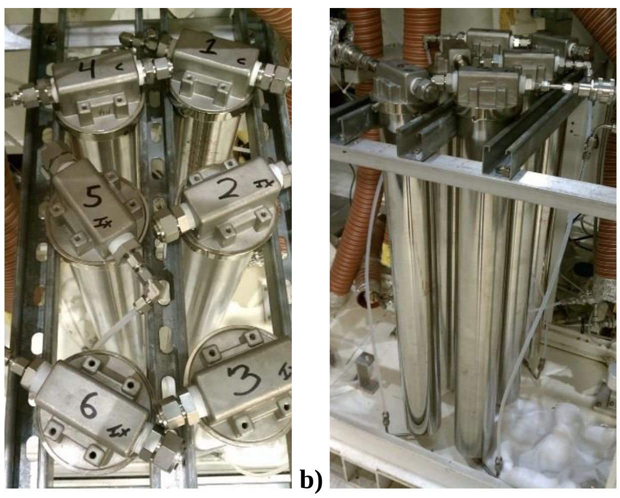
Third, the WPA MF Beds require a significant resupply mass to support WPA operation. This resupply penalty is even greater at this point on ISS because of the emergence of dimethylsilanediol (DMSD) in the WPA waste water, which is not readily removed by the WPA and therefore requiring replacement of both MF Beds more frequently than the expected nominal replacement of a single MF Bed. There is an ongoing effort to address DMSD, after which the WPA engineering team will consider extending operational life of the MF Beds based on allowing the initial ionic breakthrough products to pass through the MF Beds and be removed by the Catalytic Reactor. This operational concept is discussed in more detail below.

C. Extending Operation Life of the Multifiltration Beds

The in-flight MF Bed performance has displayed unexpected ionic breakthrough behavior characterized by an approximate 10 µmho/cm increase in conductivity after 3,200 L throughput which was then sustained for the remaining MF Bed life (*typically approximately 5,000 L due to TOC breakthrough of dimethylsilanediol, a separate issue* [2]). This behavior contrasts the expected sharp ionic breakthrough curve observed in ground tests, characteristic of normal bed performance. Furthermore, post-flight ground testing of ISS MF beds found only 40% mineral utilization of the ion exchange resin. Both of these observations indicate that a better understanding of the MF Bed performance is warranted and necessary to reduce resupply costs and increase ORU lifetime.

Previous MF Bed ground test results indicated initial ionic breakthrough was due to the bicarbonate ion (HCO_3^-). It is hypothesized that significantly more MF bed life can be achieved by allowing this contaminant to saturate both MF beds. This operational change would introduce bicarbonate to the downstream Catalytic Reactor where it is already a by-product of the reactor's oxidation process. Likewise, it is believed that the next ionic breakthrough product will be acetate ($C_2H_3O_2^-$), which is also a by-product of the reactor's oxidation process. Finally, the last breakthrough product is expected to be ammonium (NH_4^+), for which the Catalytic Reactor may have sufficient removal capacity. A proof-of-concept ground test of the flight catalyst was previously performed to show that the expected bicarbonate and acetate levels in the saturated MF Bed effluent were well within the reactor's oxidation capacity and that ammonium was also removed to acceptable levels without impacting overall reactor performance. [3] These results indicate that extending the operational lifetime of the MF Beds is feasible.

To fully evaluate this operational concept, two developmental MF (devMF) Beds were built at one-half scale of the total ISS flight MF Bed media volume. Each devMF Bed consisted of three series-plumbed, aggregate beds built using custom modified water filter housing canisters, as shown by Figure 5. Internal bed media retention and swell was accommodated by custom mobile media entrainment pucks. In this configuration, devMF Bed #1 and devMF Bed #2 were compromised of canister 1 - 3 and 4 - 6, respectively. The first canister in each devMF Bed was filled with a candidate carbon adsorbent media Ambersorb® 4652 (Dow) previously identified to replace the obsolete Barnebey-Cheney 580-26 activated charcoal for heavy VOC removal. [4] These beds are currently being challenged daily with Ersatz water representing the ISS waste water stream, including specific organic and inorganic constituents at flight-like conductivity and TOC content, as developed under ISS Program Office Change Request (CR) 013322. The breakthrough products will be characterized (sequence of conductivity breakthrough) to determine both the viability and operational approach for allowing bicarbonate, acetate, and ammonium to saturate both MF Beds prior to bed replacement.



a) b)

Figure 5. Developmental MF Beds showing a) top and b) side view of the test stand configuration.

D. Development of a Low Temperature Catalyst

The WPA Catalytic Reactor utilizes a thermal wet oxidation catalyst developed by Hamilton Sundstrand (now UTC Aerospace Systems, UTAS) in the early 2000s. This catalyst operates at 131 C and approximately 410 kPa to meet performance objectives. The objective of this task is to develop a catalyst that will support reactor operation at reduced temperature and ambient pressure to simplify process design and eases reliability concerns. In addition, a low temperature catalyst will address ongoing ISS issues with limited life of reactor seals at the current operating temperature and pressure. Unfortunately, operation at reduced temperature and pressure also decreases the effectiveness of the oxidation process. Specifically, temperature induced losses in oxidation rate kinetics can be expected. Furthermore, based on the proposed reduction in operating pressure, the oxygen solubility within the process water can be expected to decrease by an order of magnitude. However, in the approximately 15 years since the flight catalyst formulation development, it is not unreasonable to think that these potential losses in performance could be offset by implementation of state-of-the-art catalyst technology. These include, but are not limited to, advanced catalyst support materials, advances in the material science of catalytic materials and processing, and the implementation of new characterization methods. In any case, a robust material with an increase in catalytic activity is required to mitigate operating condition performance losses.

In response to a competitive RFP released in April 2014 titled "ISS Water Processor Assembly Ambient Catalytic Reactor Catalyst Development," contracts were awarded to two contractors: UTAS and Umpqua Research Company. A development effort for a new catalyst is currently underway and set to be delivered to MSFC in early 2016 for rigorous testing and evaluation. Performance goals for effluent TOC and a required ersatz water definition were provided for benchmarking catalyst activity.

IV. UPA Upgrades

As of May 1, 2015, the UPA had generated 20,049 lbs (9,094 kg) of distillate from crewmember urine since becoming operational in 2008. A total ORU mass of 4,143 lbs (1,879 kg) has operated in the UPA over the past 7 years. This includes initial hardware installation, replacements of failed ORUs, and improved hardware like the ARFTA. Overall, the UPA hardware replacement rate is currently 0.21 lbs of hardware per 1 lbs of distillate that has produced. In the pursuit to reduce replacement rates further by improving robustness and durability, several candidate upgrades are being explored. Some design features being investigated have not contributed to on-orbit failures, but would extend life or improve manufacturability. Advanced materials have also become available since the initial design and development of the UPA have suggested opportunities to increase the durability of key components. Once developed, these upgrades will be incorporated into ISS UPA ORUs to collect extended performance demonstration in an operational flight environment. Successful demonstrations will provide tangible life cycle cost benefits to the ISS over its remaining operational life and increase confidence that the UPA design can meet demanding exploration mission needs.

A. Parametric Test and Thermal Model

The development of the VCD technology primarily occurred at Life Systems International (LSI) in the 1980's based on an empirical test effort. Though the VCD technology has operated well on ISS, the UPA engineering team believes performance can be improved by optimizing the system operation. To improve the overall understanding of the system operation, a parametric test is underway to evaluate multiple operational parameters of the VCD. These parameters include the system pressures and temperatures, motor currents, production rate, and distillate conductivity and quality. In addition to the standard pressure and temperature instrumentation, the DA was also outfitted with remote temperature sensors installed inside the evaporator and stationary bowl to provide insight into the thermal transients during VCD operation.

In parallel with this effort, the MSFC Thermal Modeling Branch (EV34) is developing a fluids and thermal model of the VCD using Comsol modeling package to demonstrate and predict VCD performance. The model will be correlated using data from the parametric test and ultimately used to identify the optimal operating conditions for the VCD. In addition, the model will be used to predict if the DA size can be reduced (either length or diameter) while maintaining production rate and distillate quality. If viable, this information may be used to manufacture a smaller DA that is more advantageous for future manned missions in which available mass and volume is limited. An initial model of the DA is shown below in Figure 6.

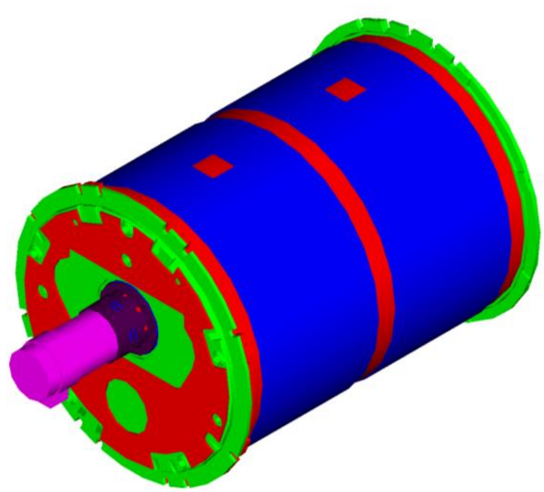


Figure 6. DA Parametric Model

B. FCPA and PCPA Valve Design

There are 3 valves that change fluid direction on the FCPA manifold. These valves undergo an iterative assembly process to incrementally achieve proper packing preload. This iterative process takes approximately 10 days per iteration with a minimum of two iterations to achieve the desired preload. The current design includes a static preload that has been found to decay during thermal cycle environmental testing, requiring more manufacturing time required.

The new design has been implemented starting in FCPA SN002-R2, which was brought up to ISS on the SpaceX 6 flight in April. Belleville washers have been added, to keep a dynamic preload on the valve packing. Removing the iterative nature of the FCPA valve packing process will save MSFC manufacturing time and make the packing more reliable against cold flow.

C. FCPA and PCPA Drive Train

FCPA life has decreased drastically in UPA ISS operation, compared to the originally predicted life that was determined based on peristaltic tubing wear out. The majority of FCPA failures have been attributed to a variety of issues found in the drive train of the FCPAs. FCPAs and PCPA both have the same drive train design, but operate at different speeds. PCPA SN001 and SN002 have failed with tube rupture signature, the expected failure for the peristaltic pumps. It is unclear why the drive train issues have been seen so frequently in the FCPA, but not in the PCPA.

The currently Mean Time Between Failures (MTBF) of an FCPA is 600 operating hours, which is currently about 3 or 4 months on ISS processing from both the US and Russian segment. To increase the life of the FCPA back up to the expected 8760 hours, a drive train redesign is currently being tested in the MSFC ground UPA developmental test bed FCPA and PCPA.

The new design moves away from the current harmonic drive design to a planetary gear drive system. The harmonic drive is designed for precision, but the planetary gear is a better design for power transfer. Once there is enough run time in the developmental ground test to prove that the planetary gear drive will work in our peristaltic pumps, MSFC will pursue the new design for the flight units. The development testing must run four times longer than the expected MTBF before it can be installed for flight; the 2400 hours will be reached with the FCPA in the summer of 2015.

D. DA Compressor and Centrifuge Bearings

The first DA failure on-orbit was due to a loss of press fit in the centrifuge bearing after 114 operating hours. There are two types of bearings in the DA: the centrifuge bearings made of hastelloy and the compressor bearings made of cronidur 30. These materials were chosen for their strength in handling the heavy DA rotational loads, and were shown to be corrosive resistance to the harsh DA environment. (See Figure 7 for previous corrosion found during testing from nominal operation.) The hastelloy bearings were found to be soft enough that they lost their press fit after multiple installations on to the shaft. After this failure, procedures were updated to restrict use of bearings to one installation with no reuse permitted. Concern of the press fit loss extended to the cronidur bearings as well to cover the uncertainty of a similar future failure in the compressor.

Other materials with similar strength and corrosive resistance as bearings were pursued, and led the team to nitinol bearings created out of Goddard Research Center (GRC). Nitinol centrifuge bearings were tested in the development DA, but were found to be cracked after 253 hours of operation. After the damage was found, the nitinol bearings were replaced with the hastelloy bearings, and further testing was suspended to allow MSFC to carry out parametric testing.

Figure 7. Corroded DA Centrifuge Bearing

E. DA O-ring Belt

Rotation of the DA is currently driven by an O-ring belt (Figure 8), but with the smooth belt in a steam environment, there is a risk of the belt slipping during operation. The risk is greatest at the beginning of a process run, since the steam has time to condense as the DA cools between processing, and this is something that has been see infrequently in ISS UPA data. To lessen the risk of slipping, a belt with teeth, such as gates of v-type belt, would increase reliability. The design change was evaluated with the new belt and required addition of a tensioner, but the concept was shelved due to limited space available for the tensioner location. Incorporation of this technology would drive an enlargement of the DA, which is considered unacceptable for the DA upgrades.

Figure 8. DA O-ring Belt

F. DA Liquid Level Sensor

The current design of the liquid level sensor (see Figure 9) is not adequate for microgravity operation. The sensor is installed pointing towards the DA wall with the purpose to alert and shutdown the UPA if the DA fluid layer becomes too thick, thereby preventing a flooding event. False high liquid level readings are regularly seen in the microgravity environment, and the UPA ignores this pass/fail sensor on ISS since the readings are misleading. False positives can be seen when splashing occurs and droplets get on the sensor. Also, if the fluid dries and scales over the sensor tip, it will show a false negative. A redesign of the sensor tip is in work to quickly let fluid slip off so sensor readings are consistent.

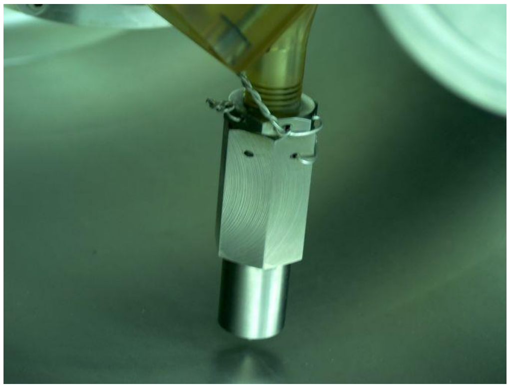


Figure 9: DA Liquid Level Sensor

G. DA Compressor Gears

The compressor gears are the current life-limiter of the DA, shown in **Error! Reference source not found.**. There are two gears, one 316L stainless steel and one vespel, with the vespel designed to wear throughout use. The expected life of the DA is 4380 operating hours. DA SN001R, recently replaced at the end of April 2015, reached 123% of its expected life and was installed for 5 years. For the last year of operation with DA SN001R, gear wear was observed by rising compressor temperature and lower production rate in ISS UPA data. The decision was made to replace it with SN002R, an on-orbit spare, because the production rate dropped from its nominal 3.5 lbs/hour to 2.5 lbs/hour over those years. This drop extended processing time by a third, therefore accelerating wear of other ORUs. Extending the life of the gears, and therefore the life of the DA, will be advantageous for deep space human missions.

Exploring alternate materials led to assessment of two zylan-coated nitinol gears from GRC that were tested in the development ground DA. The coating on these gears wore off upon first operation at MSFC, and further development was halted.

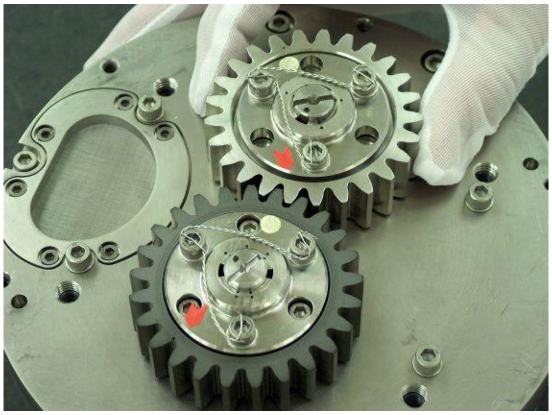


Figure 10. DA Compressor Gears

V. Conclusion

Though the initial operation of the WPA and UPA on ISS has been acceptable, improvements are highly desirable to optimize their performance on ISS and position them for use on future missions. The WPA improvements focus on reducing the resupply penalty for the WPA MF Beds and improving system reliability through the use of an improved catalyst that can operate at ambient pressure. UPA improvements are solely focused on improving system reliability by addressing known design issues currently identified from operation on ISS and manufacturing processes. Successful implementation of these upgrades will position the WPA and UPA technologies for optimum performance on ISS and execution in future manned mission beyond ISS.

Acknowledgments

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